Magnetic Combinatorial Thin-Film Libraries

Stephen E. Russek, William E. Bailey, George Alers, and Dan L. Abraham

***Abstract*—Magnetic combinatorial libraries have been fabricated to investigate complex magnetic thin-film systems and to provide test samples for the development of on-wafer metrologies. The use of combinatorial materials techniques is a new and powerful method to develop and investigate magnetic thin-film systems that require ternary or quaternary alloys. Libraries were fabricated by co-depositing $Ni_{0.8}Fe_{0.2}$, Co, and Tb in a configuration designed to provide compositional gradients across the wafer. The initial libraries consist of 20×20 sites, each marked with an identification number. The composition varies across the wafer, with compositions of $Tb_{0.60}(NiFe)_{0.10}Co_{0.30}$, $Tb_{0.22}(NiFe)_{0.22}Co_{0.56}$, $Tb_{0.10}(NiFe)_{0.65}Co_{0.25}$ at the Tb, Co, NiFe rich corners respectively. The purpose of this particular library was to investigate optimal magnetostrictive thin films that have large magnetostriction yet relatively small saturation fields, and to look for compositions that have large magneto-optical effects.**

***Index Terms*—Combinatorial libraries, magnetostriction, on-wafer metrology.**

I. Introduction

COMBINATIORIAL techniques [1] have been used to develop polymer, high dielectric constant [2], ferroelectric [3], and superconducting materials [4], [5]. In particular, combinatorial chemistry is a rapidly expanding field that is providing systematic techniques to develop and characterize new materials [6]. Application of combinatorial techniques to magnetic systems is lagging, even though multicomponent magnetic systems are, in many ways, ideally suited for combinatorial techniques. The magnetic data storage and magnetoelectronics industries increasingly rely on complex multicomponent material systems for a variety of functions such as media, shields, write poles, giant magnetoresistance and magnetic tunnel junction sensors. The effort to optimize complex material systems with 4 to 8 elements and a complicating processing parameter space will require increasing time and resources. A systematic approach, both in the fabrication and characterization of complicated magnetic thin-film systems, will be required if the present rate of technological improvement is to be maintained.

In this paper we describe the fabrication and characterization of TbNiFeCo combinatorial libraries. This system was chosen because it may contain regions that exhibit giant magnetostrictive properties [7] and contains a region similar to the rare-earth/transition-metal systems that were developed for magneto-optical recording [8]. Regions of interest include compositions that exhibit large magnetostriction with a low saturation field and regions that have large magneto-optical Kerr effect (MOKE). Films with large magnetostriction and low saturation fields may have applications for MEMS-based actuators and transducers.

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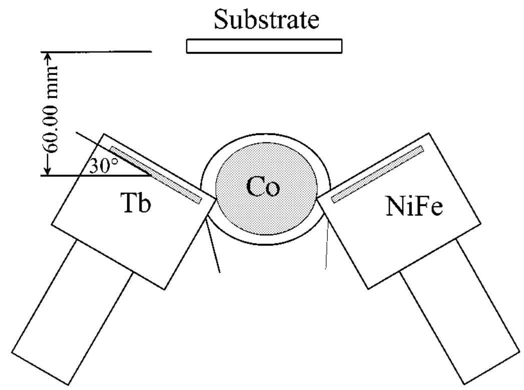

Fig. 1. Schematic of sputter deposition geometry showing three of the four focused sputter guns. Not shown are the shields that prevent cross-contamination of the targets.

II. Experiment

Metal-alloy films were magnetron-sputter-deposited at room temperature in a system with four focused sputter guns as shown in Fig. 1. For the present libraries, Tb, $Ni_{0.8}Fe_{0.2}$, and Co targets were used on three guns; the fourth gun was left blank. The deposition rates across the 3-inch wafer were calculated from single-source calibration runs using a profilometer as shown in Fig. 2. The variation along the deposition axis is approximately linear while the variation perpendicular to the deposition axis is weaker and roughly quadratic. The individual-element deposition rate varies by a factor of 5 across the wafer. The amount of composition variation can be controlled by changing the height of the substrate above the targets. The deposition rates for each individual gun were fitted with a second-order polynomial and the nominal compositions were calculated by assuming that the rates for each gun, when they were operating together, were the same as when they were operating in isolation.

For the present libraries the compositions at the element-rich corners were approximately 60%, falling to 10% at the element-poor corner (see Fig. 3). The films thickness also varied across the wafer with approximately a 40% variation from the center to the edge of the wafer. If four guns were used it would be possible to maintain a better thickness uniformity across the wafer while having large composition gradients.

The libraries were fabricated using standard optical lithography and either wet or dry etching (see Fig. 4). The sites were 2 mm squares on a 2.5 mm grid. Identification numbers were

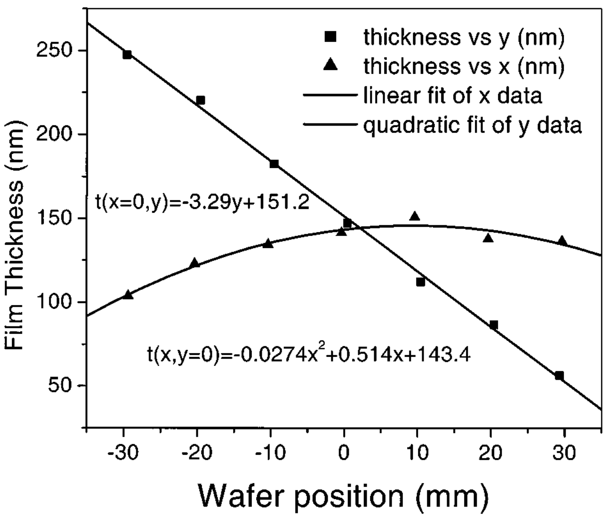

Fig. 2. Single-element (NiFe) thickness calibration across the wafer. The composition decreases linearly in the y direction, along the plane of incidence. The composition is weakly varying and parabolic in the x direction, perpendicular to the plane of incidence.

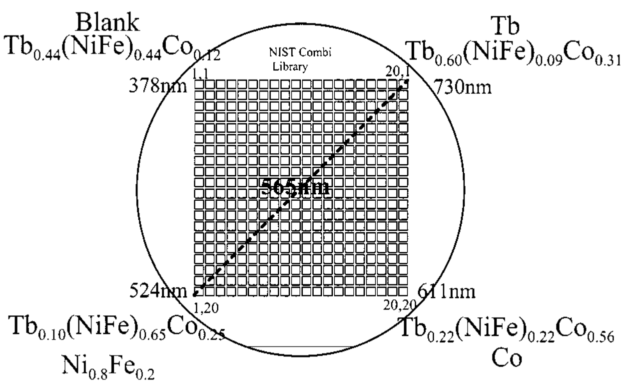

Fig. 3. Composition and thickness variation across a particular magnetic library. The dashed line indicates the region for which the magnetic data in Fig. 5 was taken.

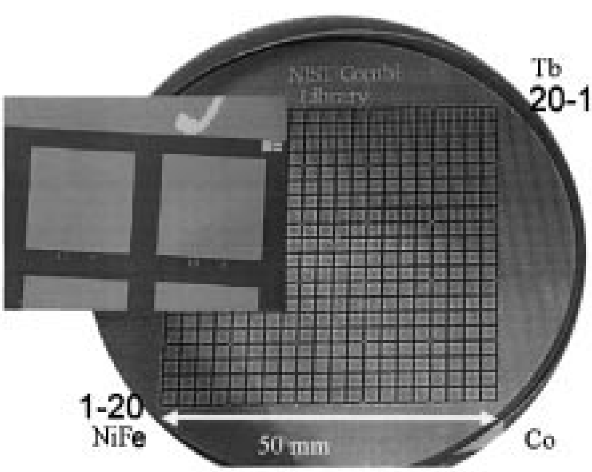

Fig. 4. Photograph of magnetic combinatorial library showing 2 mm sites with identification numbers.

added by depositing a thin Au layer using a lift-off process. Some libraries were passivated by terminating the depositions in a thin layer of NiFe and some were left unpassivated. Studies of corrosion properties of the different sites on the libraries may potentially have as much value as the study of magnetic properties.

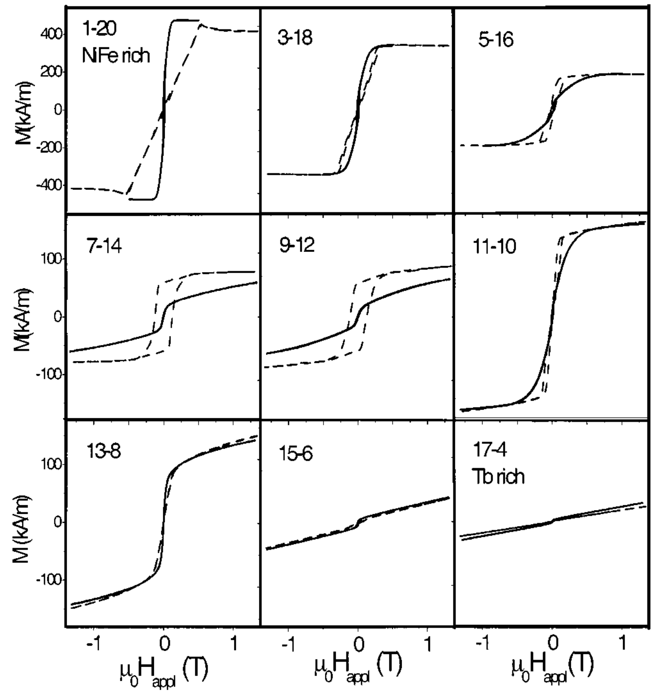

Fig. 5. In-plane (solid) and perpendicular (broken) hysteresis loops along NiFe–Tb diagonal. A transition to perpendicularly magnetized films occurs at site 5-16. A transition to an isotropic phase occurs at site 13-8. Note that only every other site along the diagonal is displayed.

Some of the libraries were left whole for on-wafer measurements, while others were diced up to allow the use of conventional measurement techniques. The magnetic properties on the diced samples were measured using an alternating gradient magnetometer (AGM). The on-wafer measurements were performed with a scanning magneto-optical Kerr effect (MOKE) system in the longitudinal geometry. In this configuration the MOKE signal is proportional to an admixture of the in-plane and out-of-plane magnetization. For all of the sites examined, there was no in-plane anisotropy. For many systems, strong magnetic anisotropies can be induced by deposition at angles off normal. In the present case, while the flux from each element comes in at a fixed angle ($\sim 30°$ off normal), the total flux has approximate in-plane symmetry.

III. Results

Fig. 5 shows the room-temperature hysteresis loops, measured with an AGM, for both in-plane and out-of-plane applied fields along the NiFe–Tb diagonal. The response in the NiFe rich corner shows a small in-plane coercivity and a hard axis out of plane, as expected. As the Tb content increases (the Co content is relatively fixed), the saturation magnetization decreases. The Tb moment aligns antiparallel to the transition-metal magnetization and reduces the total net moment [8], [9]. The slope of the hard-axis loops decreases as the Tb content increases, indicating that there is an increase in anisotropy energy favoring perpendicular magnetization. At site 5-16 there is a transition

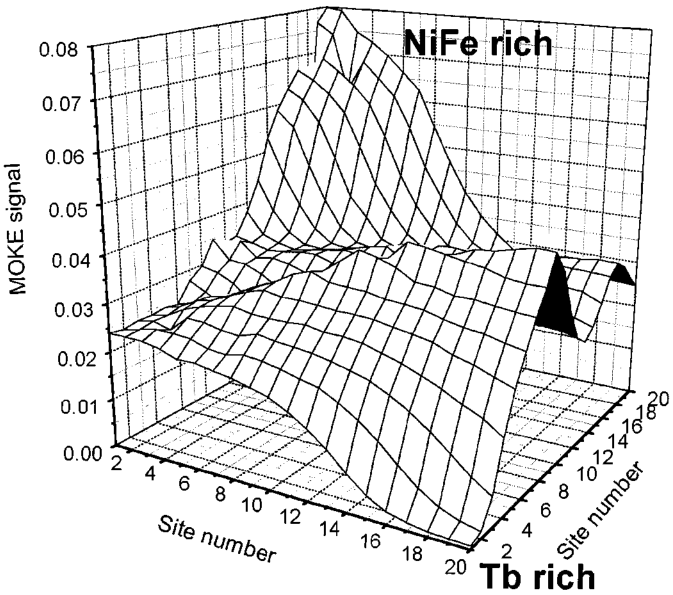

Fig. 6. Scanned MOKE map of the combinatorial library showing the MOKE signal in a 0.06 T in-plane field.

from in-plane orientation at zero field to an out-of-plane orientation. The perpendicular anisotropy continues to grow, as evidenced by the larger in-plane saturation fields and the increasing out-of-plane coercivity. At site 13-8 a transition to an isotropic phase occurs with no well-defined easy or hard axis. As the Tb rich corner is approached the hysteresis loops approach paramagnetic behavior, as expected. A map of the MOKE signal, with an applied in-plane field of at 0.06 T, is shown in Fig. 6. Quantitative interpretation of the MOKE data is difficult due to the lack of saturation for many of the sites at 0.06 T and due to the variation of magneto-optical properties across the library. The MOKE data does, however, give a qualitative map of the library. The soft NiFe rich corner gives the largest MOKE signal due to its large easily-saturated in-plane moment. The central plateau contains the region of perpendicular magnetization and the rapid fall off in the MOKE signal at the Tb rich corner indicates the onset of paramagnetic behavior.

IV. Discussion

The data in Fig. 5 illustrate several challenges to magnetic combinatorial measurements. First, there can be a wide range of properties on a single library. The coercive fields, for the library measured in Fig. 5, range from 0.3 mT to 300 mT. Further, to ascertain the magnetic structure, the magnetic fields must be applied in several directions; and it is not clear, *a priori*, which field directions will be the most relevant. The measurement system must be intelligent enough to deduce what range of measurements is pertinent for a given site.

While several on-wafer measurement techniques exist at present, they are not sufficient to fully characterize magnetic libraries. Scanned MOKE, for instance, must be combined with a local measurement of saturation magnetization to provide complete magnetic characterization. Local on-wafer measurements of magnetostriction are not yet available. We are presently working on noncontact magneto-acoustic techniques to measure magnetostriction. These techniques use electromagnetic acoustic transducers and magnetostrictive coupling to launch and detect surface acoustic waves.

In summary, we have fabricated magnetic combinatorial libraries to assess the viability of combinatorial techniques for use in magnetic data storage and magnetoelectronic applications. The initial TbNiFeCo libraries show a rich variety of magnetic properties and illustrate many of the challenges that will be faced when developing tools to systematically characterize magnetic libraries.

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